Autonomous VTOL Scalable Logistics Architecture (AVSLA)

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AVSLA is a Transportation System Solution

The Problem

Delays
Pollution
Congestion

The Solution
Phase II Team
What We’ll Discuss

• Background
• Phase I Objectives
• Phase I Results
• Phase II Objectives
• Phase II Plan
Expanding Transportation Capacity is a BIG Problem

“Despite significant progress, a transportation system that serves a growing America still requires more capacity [and] performance. The transportation solutions of the past – building more roads, bridges and airports – can no longer be our first choice … It’s too expensive and too damaging to our communities and our environment … A total of $39.8 billion is proposed for transportation mobility programs…”

*from the U.S. Dept. of Transportation FY2000 Budget in Brief
Phase I Performed by Sikorsky Aircraft

- Limited funding for identifying important issues and examining concept feasibility.
  - Plan presented: June, 2000.

- Phase I results showed promise for concept.

- Phase II benefits from synergistic teaming of Sikorsky and GIT’s Aerospace Systems Design Laboratory.
What’s Next?

- Background
- Phase I Objectives
- Phase I Results
- Phase II Objectives
- Phase II Plan
Phase I Focused on a New Logistics Architecture

- Based on Autonomous air transport.
  - VTOL aircraft provide flexibility and reduce infrastructure investment.

- Broad system focus, not specific technologies/vehicles.

- First pass at determining system feasibility.
  - Economic
  - Technical
  - Socio-political

- Focused on Northeastern U.S. region.
What's Next?

• Background
• Phase I Objectives
• Phase I Results
  – Operations Analysis
  – System Definition
  – Vehicle Definition
  – Economic Competitiveness
• Phase II Objectives
• Phase II Plan
### 3.6 Million Tons of Cargo Shipped in the Northeastern U.S. Every Day

Seven Commodities with Value Densities > $10/lb.

<table>
<thead>
<tr>
<th>SCTG Code</th>
<th>Description</th>
<th>V/T [$/lb.]</th>
<th>% Total Value Shipped</th>
<th>% Total Tons Shipped</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>Precision instruments and apparatus</td>
<td>68</td>
<td>3.3</td>
<td>0.0</td>
</tr>
<tr>
<td>21</td>
<td>Pharmaceutical products</td>
<td>35</td>
<td>6.0</td>
<td>0.2</td>
</tr>
<tr>
<td>35</td>
<td>Electronic, electrical equipment/components, office equipment</td>
<td>29</td>
<td>13.2</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>Tobacco products</td>
<td>18</td>
<td>0.6</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>Textiles, leather, and articles of textiles or leather</td>
<td>14</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>37</td>
<td>Transportation equipment</td>
<td>14</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>34</td>
<td>Machinery</td>
<td>11</td>
<td>5.4</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>35.5</strong></td>
<td><strong>1.4</strong></td>
</tr>
</tbody>
</table>

There is **$2.3 BILLION** worth of these goods on the road each day.

Aircraft will be able to compete in markets with high value densities.
A Look At The Competition In The NE

- Light aircraft designed to deliver a 100 lb. payload 500 miles.
- Heavy lift aircraft designed to deliver a 10,000 lb. payload 250 miles.

**Total Tonnage Transported in NE**
- Trucks 86%
- Other 13%

**Fact:** 55% of Truck Deliveries are < 10,000 lb.

**Fact:** 60% of Postal & Courier Deliveries are < 100 lb.

**Total Value Transported in NE**
- Trucks 71%
- Other 10%

**Distances By Post Office & Courier**
- < 500 miles 60%
- > 500 miles 40%

**Distances By Truck**
- < 250 miles 91%
- > 250 miles 9%

**Distances Between 500 & 100 miles**

**Distances Between 250 & 100 miles**

**Distances Less Than 100 miles**

**Fact:** 55% of Truck Deliveries are < 10,000 lb.

**Fact:** 60% of Postal & Courier Deliveries are < 100 lb.
The Current Transportation System is Expensive

- **Direct Expenses**
  - Fuel / parts
  - Labor
  - Capital

  - $125.3B per annum on road and bridge construction. Most pavement costs directly related to damage caused by heavy vehicles.*

Don’t Forget Indirect Costs

- ~6,400 highway deaths (11% of total) attributed to commercial trucks annually.
- Highway vehicles responsible for 62% of CO emissions, 32% of NO$_x$, and 26% of VOCs.
- $4.2B per annum for tire, oil, and battery disposal.
- Traffic congestion estimated to cost $182B per year.
- Crash costs estimated to be $840B per year.
- Trucks are responsible for ~1/3 of these totals: $340 B

Sources: EPA and DoT reports.
## AVSLA Savings Potential

### AVSLA System Cost Savings

<table>
<thead>
<tr>
<th>Factor</th>
<th>Total Trucking Costs (Millions $)</th>
<th>(Replace 1.76% of trucks in region) (Millions $)</th>
<th>* Assumed Percentage Of Trucking Costs</th>
<th>AVSLA System Costs (Millions $)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infrastructure</strong></td>
<td>$ 14,114</td>
<td>$ 248</td>
<td>0%</td>
<td>$ -</td>
</tr>
<tr>
<td><strong>Indirect Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Pollution</td>
<td>$ 1,868</td>
<td>$ 33</td>
<td>50%</td>
<td>$ 16.4</td>
</tr>
<tr>
<td>Greenhouse Gases</td>
<td>$ 2,968</td>
<td>$ 36</td>
<td>25%</td>
<td>$ 9.1</td>
</tr>
<tr>
<td>Water</td>
<td>$ 858</td>
<td>$ 15</td>
<td>25%</td>
<td>$ 3.8</td>
</tr>
<tr>
<td>Noise</td>
<td>$ 1,209</td>
<td>$ 21</td>
<td>50%</td>
<td>$ 10.6</td>
</tr>
<tr>
<td>Waste Disposal</td>
<td>$ 92</td>
<td>$ 2</td>
<td>25%</td>
<td>$ 0.5</td>
</tr>
<tr>
<td>Congestion</td>
<td>$ 5,594</td>
<td>$ 98</td>
<td>0%</td>
<td>$ -</td>
</tr>
<tr>
<td>Crash Costs</td>
<td>$ 16,856</td>
<td>$ 297</td>
<td>0%</td>
<td>$ -</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$ 42,659</td>
<td>$ 751</td>
<td></td>
<td>$ 40.4</td>
</tr>
</tbody>
</table>

**$710 Million Saved in Northeast alone!**
What’s Next?

- Background
- Phase I Objectives
- Phase I Results
  - Operations Analysis
  - System Definition
  - Vehicle Definition
  - Economic Competitiveness
- Phase II Objectives
- Phase II Plan
Delivery Network Topology Design Space
**System Scheduling Design Space**

- **Scheduled service**
  - Follow a pre-determined schedule
  - Analogous to a railroad

- **Posture-based service**
  - Response based on location of assets
  - Quarterbacks make these kinds of decisions

- **Priority-based scheduling**
  - Response based on priority of event triggers
  - Think of triage in an emergency room

- **Predictive-Adaptive Scheduling**
  - Prepare for expected demand, but be flexible
  - Similar to restaurant employee scheduling
Control Concept Design Space

- Centralized Control
- Regional Control
- Fully Distributed
- Dispatch Control
What's Next?

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- Phase I Objectives
- Phase I Results
  - Operations Analysis
  - System Definition
  - Vehicle Definition
  - Economic Competitiveness
- Phase II Objectives
- Phase II Plan
Light Vehicle Design

Current Tech: 35 lb. payload, 230 miles, 120 knots

Future Tech: 100 lb. payload, 500 miles, ~140 knots
Heavy Lift Vehicle Design

- Will be studied in Phase II
- Two options for approaching heavy lift:
  - Automate an existing manned helicopter
    - Economies of scale
    - Limited development costs – only developing flight control.
    - Reduced risk
  - Clean sheet design
    - Better performance
    - Tailor fit for customer requirements
    - Expensive
What's Next?

- Background
- Phase I Objectives
- Phase I Results
  - Operations Analysis
  - System Definition
  - Vehicle Definition
  - Economic Competitiveness
- Phase II Objectives
- Phase II Plan
Economic Comparison

**Capital Costs**

<table>
<thead>
<tr>
<th>Basic Comparison of Vehicle Cost (Excluding Financing Costs)</th>
<th>1-Package VTOL</th>
<th>Current Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packages per Day</td>
<td>1,500,000</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Packages per Hour</td>
<td>187,500</td>
<td>187,500</td>
</tr>
<tr>
<td>Vehicle Cost (each)</td>
<td>$4,000.00</td>
<td>$50,000.00</td>
</tr>
<tr>
<td># of Vehicles Needed</td>
<td>187,500</td>
<td>8,600</td>
</tr>
<tr>
<td>Total Cost of All Vehicles</td>
<td>$750,000,000.00</td>
<td>$430,000,000.00</td>
</tr>
<tr>
<td>Vehicle Life (years)</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Vehicle Cost per Year</td>
<td>$93,750,000.00</td>
<td>$35,833,333.33</td>
</tr>
<tr>
<td>Vehicle Cost per Day</td>
<td>$360,576.92</td>
<td>$137,820.51</td>
</tr>
<tr>
<td>Vehicle Cost per Package</td>
<td>$0.24</td>
<td>$0.09</td>
</tr>
</tbody>
</table>

**Operational Costs**

<table>
<thead>
<tr>
<th></th>
<th>Delivery Van</th>
<th>Light AVSLA</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>0.12</td>
<td>0.12</td>
<td>$/pkg-hr</td>
</tr>
<tr>
<td>Misc. Finance Cost</td>
<td>1.02</td>
<td>1.08</td>
<td>$/pkg-hr</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.19</td>
<td>0.25</td>
<td>$/pkg-hr</td>
</tr>
<tr>
<td>Personnel</td>
<td>1.40</td>
<td>0.43</td>
<td>$/pkg-hr</td>
</tr>
<tr>
<td>Total Operations Cost</td>
<td>2.73</td>
<td>1.88</td>
<td>$/pkg-hr</td>
</tr>
<tr>
<td>Speed</td>
<td>15</td>
<td>90</td>
<td>mph</td>
</tr>
<tr>
<td>200-mile delivery time</td>
<td>13.33</td>
<td>2.22</td>
<td>hr</td>
</tr>
<tr>
<td>Operational cost for 200-mile delivery</td>
<td>36.40</td>
<td>4.18</td>
<td>$/pkg</td>
</tr>
</tbody>
</table>

**Operational savings outweigh capital costs.**
Phase I Identified Technology Roadmap Issues

- Advanced system will rely on improved information gathering and sharing.
- Communication link integrity and security is a basic requirement.
- Integration with the National Airspace will be a key issue.
- Free flight initiatives will benefit this system.
- It is necessary to both improve the vehicle technologies and reduce life-cycle costs.
What’s Next?

- Background
- Phase I Objectives
- Phase I Results
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- Phase II Plan
AVSLA Team- Phase II Goal

Autonomous VTOL Scalable Logistics Architecture (AVSLA)

“AVSLA is envisioned to be a future cargo delivery “system-of-systems” that provides cheaper, more efficient, and more effective service to the nation’s consumers. Related VTOL vehicles for military heavy-lift purposes are also likely to benefit from AVSLA technology. The stated goal of the NIAC Phase II program is to provide a sound basis for NASA to use in considering advanced concepts for future missions. Thus, this Phase II proposal focuses on specific, critical research areas identified for AVSLA.”

“The overall technical goal is to develop a system-of-systems model of the AVSLA design space, complete with supporting analyses in key areas, that, when combined with advanced probabilistic design methods, can establish a solid basis for establishing a full-scale research program at NASA.”
Phase II Partnerships

“Need UPS for realism of cost. It will take UPS involvement to be sure that the numbers are realistic”

- Collaboration established with UPS e-ventures in Atlanta
- First meeting June 18; attendees include logistics experts as well as business planners

“Working with the FAA at this point is critical; Without buy in by the FAA, any concept of this type is dead on arrival”

- Collaboration with GTRI in Atlanta and FAA in Washington
- Objectives: understand regulatory issues & emerging technologies (ADSB, etc), to leverage planning for next-generation NAS

US Army

- Contact made with AMCOM (AMRDEC)
  - Emerging Army center of excellence for UAVs
  - Interest in autonomous resupply of Future Combat System
AVSLA Knowledge-Centric Design Space

Where is the Knowledge and Control?

Today

- Dynamic Dispatch/Delivery
- Slave Routing

Centralized

Scheduling

Delivery Network Topology

Control Distribution

Fully Distributed (Point-to-Point)

Future?

- Dynamic Dispatch/Delivery
- Autonomous Flight
- Point-to-Point Network

- Autonomous Flight
- Slave Routing

Georgia Tech
Key Technical Objectives

• Develop a AVSLA system-of-systems methodology, that creates an infrastructure for continued study:
  • Expand the system dynamics model to explore National (NE + SE) & Urban settings
  • Create ability to trade-off different network topologies, control technologies, etc.
  • Create ability to account for “dynamic markets”, i.e. answer the question “Is the given AVSLA concept robust to market changes” (Business Plan)

• Understand technology co-evolution!
  • Any future delivery architecture will have to co-evolve with legacy delivery systems and transportation infrastructure
  • AVSLA will not magically appear all at once
  • Understand and model capital cost and ATC constraints related to transition
  • Consider the creation of new markets to speed transition (business innovation!)

• Understand fundamental issues in package delivery
  • Cost Drivers!- Number of touches, direct operating costs
  • Hub/Spoke Operation; Sorting functions, technologies, bottlenecks
  • “Transition time” costs/implications

FAA/GTRI Partnership

UPS Partnership
Key Sub-Areas of Research

• Onboard vehicle computing (Comm/Nav/FCS)- How much?
  – Finding in Phase I- For the small VTOL, it is critical to determine which capabilities are feasible “on-board” in point-to-point architecture

• Reliability of Autonomous Service/Control
  – Dr. G. Vachtsevanos (GT-EE), Vehicle Autonomy/QoS Expert

• NAS/ATM System Integration
  – Number 1 Issue for AVSLA, from a safety and public acceptance point of view
  – C. Stancil (GTRI) and FAA expertise

• Transportation Architecture Scalability (up and down)
  – NE Region modeled in Phase I
  – Do the dynamics change in national-scale model (NE+SE) ??
  – Do the dynamics change in urban setting ??
Exploring The Economy Of The Southeast

- The South Atlantic division of the South region
  - (Delaware, DC, Florida, Georgia, Maryland, N&S Carolina, Virginia, W. Virginia **9 states**)
- Which commodities offer the best combination of **value density, market size, and market growth**?
- How are these commodities delivered?
- How far are these items shipped?
- How large are the shipments?
Determining The Ideal Commodities For Delivery...

- Value density, growth, total value combined into a single “goodness” indicator
- Each metric is normalized

\[
Value_{A \ (Normalized)} = \frac{Value_A}{\sqrt{Value_A^2 + \ldots + Value_Z^2}}
\]

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Total Value</th>
<th>Value Density</th>
<th>Market Growth</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobacco</td>
<td>0.15</td>
<td>0.26</td>
<td>-0.21</td>
<td>0.228</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>0.24</td>
<td>0.32</td>
<td>0.39</td>
<td>1.044</td>
</tr>
<tr>
<td>Textiles</td>
<td>0.70</td>
<td>0.13</td>
<td>-0.03</td>
<td>0.826</td>
</tr>
<tr>
<td>Electronics &amp; Office Eq.</td>
<td>0.57</td>
<td>0.44</td>
<td>0.35</td>
<td>1.480</td>
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<tr>
<td>Transportation Equipment</td>
<td>0.08</td>
<td>0.38</td>
<td>0.01</td>
<td>0.543</td>
</tr>
<tr>
<td>Precision Equipment</td>
<td>0.11</td>
<td>0.64</td>
<td>0.48</td>
<td>1.406</td>
</tr>
<tr>
<td>Industrial Machinery</td>
<td>0.29</td>
<td>0.24</td>
<td>0.63</td>
<td>1.268</td>
</tr>
<tr>
<td>Furniture</td>
<td>0.10</td>
<td>0.11</td>
<td>-0.22</td>
<td>-0.014</td>
</tr>
</tbody>
</table>
Determining The Ideal Commodities For Delivery...

- Target Commodities:
  - Pharmaceuticals
  - Industrial Machinery
  - Precision Equipment
  - Electronics & Office Equipment

For The NE, you may recall:
- **Heavy vehicle**
  - 10K lb. payload
  - 250 statute mile range

- **Light vehicle**
  - 100 lb. payload
  - 500 statute mile range

* Primary Data Source: 1997 Commodity Flow Survey, South Atlantic Division, U.S. Dept. of Transportation April 2000
Structured Design Methodology Provides Critical Functions

- Ability to explore, compute, and visualize sensitivities of key AVSLA objectives to:
  - Economic and Regulatory requirements
  - Vehicle and Information technologies
  - System architecture variables

- It is critical to quantify and track RISK from the beginning in order to realize the advanced AVSLA concept
  - A credible technology roadmap, including risk, is essential for NASA to consider funding in base R&T

- Design Decision Documentation
Methodology for Continuous Design/Development

1. **Problem Definition**
   - Identify objectives, constraints, design variables (and associated side constraints), analyses, uncertainty models, and metrics

2. **Determine System Feasibility**
   - Constraint Fault Tree
   - Physics-Based M&S+FPI
   - P feas \(<\) \(\varepsilon\) small

3. **Examine Feasible Space**
   - Design Space Model
   - AVSLA Systems Dynamics Model
   - Relax Active Constraints?

4. **Technology Identification/Evaluation/Selection (TIES)**
   - Identify Technology Alternatives
   - Collect Technology Attributes
   - Form Metamodels for Attribute Metrics through Modeling & Simulation
   - Employ Tech. Confidence Shape Fcns.
   - Probabilistic Analysis to obtain CDFs for the Alternatives
   - Obtain New CDFs

5. **Decision Making**
   - MADM Techniques
   - Robust Design Simulation
   - Incorporate Uncertainty Models

The “UTE”

It is at this critical decision-box that we need to examine requirements, potential technologies, and concepts.
### Concept Alternative Generation

**Example:**
- **Point-to-Point Topology**
- **Single Vehicle System**
- **Docs+Small Parcel**
- **Express Service**
- **Auton. VTOL**
- **50-500 miles**
- **Real-time pkg track**
- ..........

<table>
<thead>
<tr>
<th>Horizontal Delivery System Topology</th>
<th>Hub &amp; Spoke</th>
<th>Point-to-Point</th>
<th>Hybrid Distributed</th>
<th>Dynamic Network Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Delivery System Topology</td>
<td>Single, All-Purpose Vehicle</td>
<td>Separate Delivery Vehicle and Transfer Vehicle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Type</td>
<td>Document</td>
<td>Standard Mail</td>
<td>Small Parcel (&lt; 50lbs, &lt; 2x2x2 ft)</td>
<td>Freight (sizes above Small Parcel)</td>
</tr>
<tr>
<td>Shipment Time</td>
<td>Same-day (SuperExpress)</td>
<td>Next-Day (Express)</td>
<td>Same-week</td>
<td>Variety</td>
</tr>
<tr>
<td>Vehicle Type</td>
<td>Fixed Wing A/C (wide-body Jet or regional turboprop)</td>
<td>Trucks and Vans</td>
<td>Autonomous VTOL-Heavy</td>
<td>Autonomous VTOL-Light</td>
</tr>
<tr>
<td>Mission (Range)</td>
<td>Urban (&lt; 50 miles)</td>
<td>Regional (50 - 500 miles)</td>
<td>National (&gt; 500 miles)</td>
<td>International</td>
</tr>
<tr>
<td>Air Traffic Control</td>
<td>Current ATC</td>
<td>ADS-B</td>
<td>ADS-B (TIS-B, FIS-B)</td>
<td>VTOL Corridors</td>
</tr>
<tr>
<td>Operation Control</td>
<td>Autonomous</td>
<td>Semi-Autonomous</td>
<td>Non-Autonomous (Slave)</td>
<td></td>
</tr>
<tr>
<td>Strategic Control (Dispatch)</td>
<td>Centralized</td>
<td>Distributed to Hubs</td>
<td>Distributed to Vehicle</td>
<td></td>
</tr>
<tr>
<td>Package Sorting</td>
<td>Current System</td>
<td>Sort at each stop/hub</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Tracking</td>
<td>No tracking</td>
<td>Update Tracking at each stop</td>
<td>GPS Tracking / per vehicle (real time)</td>
<td>GPS Tracking / per package (real time)</td>
</tr>
<tr>
<td>Number of Hand-offs</td>
<td>Two (Pickup,Delivery)</td>
<td>Three (pickup, transfer, delivery)</td>
<td>Four</td>
<td>Five</td>
</tr>
<tr>
<td>Pick-Up/Delivery Approach</td>
<td>Fixed number of standard “smart” containers</td>
<td>Customer packaging, restricted in size &amp; volume</td>
<td>Six</td>
<td></td>
</tr>
</tbody>
</table>

*So many possibilities!*  
**THOROUGH Ops/Econ Analysis and technology evaluation can reduce the “option space” to some extent*
Many Trades to Be Made---e.g. Modular “Smart” Container?

Each Row in the Morphological Matrix represents a set of trade-offs that must be made, including interaction with other rows (systems).

Example: Pick-up/Drop-off interface

1. Option 1 (Right): Modular “smart” containers, accommodating a fixed number of discrete package volumes

2. Option 2: Customer chooses packaging, places it in “smart box” similar to today’s FedEx boxes, transfer en-masse to vehicle (sorting on-board?)
Dynamic Visualization of Analyses - A Notional “Look Ahead” at AVSLA Candidates

AVSLA Figure of Merit contours set here

INTERACTIVE Slide bars control design variable values

Constraints are set here

NOT FEASIBLE

FEASIBLE SPACE

Level of VTOL Autonomy

Level of Distribution of Delivery Topology

Del. Reliability

VTOL Reliability

Market Share

Total Time

Total $$
Requirements Ambiguity + Tech. Uncertainty: Assessing RISK in AVSLA Development

One Requirement (1-D) Example

Achieved Requirement
(What Delivery Cost can AVSLA achieve in light of technology uncertainty?)

Anticipated Requirement
(What Delivery Cost will the market demand?)

Range of Satisfied Requirement
(Achieved > Anticipated)

Probability Density Function (PDF) for RD

Probability of Satisfying Delivery Cost

Cumulative Probability Function (CDF) for RD

Probability of Satisfying Delivery Cost

RD = Req_{Achieved} - Req_{Anticipated}
What’s Next?

• Background
• Phase I Objectives
• Phase I Results
• Phase II Objectives
• Phase II Plan
The Road Ahead

ATC Compliance

Customer Realism (UPS, US Army)

Autonomous Control Issues

System Dynamics

Sikorsky System Integration Expertise
Georgia Tech Design Methodology
Probabilistic Approach

Phase II Outputs
1. AVSLA Concepts with highest Probability of Success
2. Technology Roadmap
3. Research Requirements Going Forward
AVSLA is a Transportation System Solution

The Solution